THE ELECTROMAGNETIC THEORY OF LIGHT

By Professor DAVID VANCE GUTHRIE
LOUISIANA STATE UNIVERSITY

OF the many striking advances which marked the progress of physical science in the past century, two stand out as preeminently the greatest and most far-reaching—the discovery of the principle of the conservation of energy, and the promulgation and verification of the electromagnetic theory of light. Many other discoveries of the highest interest and greatest value were made, but these two stand apart as the crowning achievements of nineteenth-century physics. While a knowledge of the former of these principles has become widely diffused, we find quite the reverse to be true with regard to the latter. The "conservation of energy" has become a household phrase, while, on the other hand, there are very few to whom the "electromagnetic theory of light" is more than a meaningless expression. This lack of acquaintance on the part of the general public with one of the most interesting developments of modern scientific theory is doubtless due in large part to the fact that there has been little attempt up to the present time to present the essentials of the theory in simple form and in non-mathematical language, so as to be readily intelligible to the average well-informed reader. The story of the successive steps in the development of the theory and of the various experiments which have served to establish it on a firm basis forms one of the most fascinating chapters in the annals of modern science, and it is the purpose of the present article to recount the chief of these steps as well as to outline briefly the essential features of the theory.

The speculations of the ancients as to the nature of light strike our modern fancy as fantastic and grotesque. Many of the philosophers of antiquity advocated the view that we see bodies by means of rays proceeding from the eye to the object of vision rather than in the contrary direction. None of the theories proposed rested upon any basis of scientific fact. The first serious attempt to answer the question as to the nature of light seems to have been in the time of Newton. At this time two conflicting theories arose; the corpuscular theory, and the undulatory, or wave, theory.

Those who held to the former theory advocated the view that luminous bodies are continually emitting streams of small particles traveling with very high velocity, like tiny bullets, which, on entering the eye, produce the sensation of sight. Simple though the theory may appear at first sight, it was soon found that in its general application diffi-

culties are encountered which can only be surmounted by resorting to hypotheses which seem extremely strained and artificial. Newton himself stood sponsor for the corpuscular theory, and it is evident that the weight of his opinion maintained it in the ascendancy much longer than if it had been left to stand or fall on its own merits. Until the close of the eighteenth century this was the theory generally accepted.

The wave theory, according to which light consists of waves traveling through a medium of some sort rather than a stream of material particles, was elaborated by Newton's contemporary, Huyghens, and in many respects seemed more closely in accord with the results of experimental evidence than the corpuscular theory. At that time, however, positive evidence serving to discriminate between the two theories was lacking. Such evidence was furnished many years later by the establishment of the fact that light travels more slowly in dense than in rare media; a result in accord with the predictions of the wave theory, but directly opposed to the consequences to which the corpuscular theory would lead us. This evidence was not available in the seventeenth century, however, as no practicable method of determining the velocity of light in different media had been devised at that time. Newton seems to have been led to reject the wave theory because of the fact that light does not appear to bend around the corners of an obstacle as do sound waves or water waves. This premise we now know to have been a mistaken one, for the beautiful diffraction experiments of Fresnel proved that light does bend around the edges of a body as do other types of waves. The effect is less noticeable the shorter the length of the wave, however, and in the case of light waves is only rendered manifest by such phenomena as those of diffraction. Finally, in 1801 the wave theory became definitely established through the classic experiments of Thomas Young on interference.

To have proved that light consists of waves, however, is to have advanced only a short way toward the complete solution of the problem. It is at least equally important to settle the question as to what kind of waves light waves are. In every type of wave motion it is essential that we have a medium and a disturbance of some sort traveling through this medium. So we have not learned much as to the true nature of light until we are able to give some account of the nature of the medium which serves to convey light waves and of the character of the disturbances which are set up in it.

The questions as to the nature of the medium and the character of the disturbances are linked closely together, for upon the properties of the medium will naturally depend the type of disturbance which that medium is capable of transmitting. Certain properties of the medium which must be supposed to exist in order to account for the phenomena of light were manifest from the first; certain characteristics which

made it evident that the medium in question must differ in many respects from ordinary matter. It must fill all space and at the same time must be tenuous in the extreme, since the planets and other heavenly bodies move through it without having their motion retarded in the slightest degree. It must also be capable of acquiring and transmitting energy, both potential and kinetic. To this medium was applied the name "the luminiferous ether."

One of the most common types of wave motion is that found in elastic solid bodies, and in many respects there seemed to be a similarity between light waves and the waves in such bodies. Accordingly, the "elastic solid theory" arose, which attributed to the ether the properties of an elastic solid and assumed that ether waves were similar to the waves set up in bodies of this character. The properties of such waves are familiar and their velocity can always be expressed as a function of the density and of the elasticity of the medium. The theory furnished a simple and satisfactory explanation of the majority of optical phenomena and seemed a long step toward the solution of the problem as to the nature of light.

There were certain implications of the theory, however, which seemed to necessitate somewhat violent assumptions as to the properties of the ether. The velocity of waves in elastic bodies is $\sqrt{E/d}$, where E represents the elastic modulus of the medium and d its density. Now since light travels through the ether at the enormous velocity of 300,000 km. per second, it follows that E must be very great or d extraordinarily small. But the assumption of a medium with density far below that of any known material substance, and at the same time with elastic properties comparable with those of steel, involves obvious difficulties. Nor was this the chief difficulty. The phenomena of polarized light proved beyond a doubt that light waves are transverse waves. Nowhere was there any evidence of the existence of longitudinal waves in the ether. An elastic solid, however, must be capable of transmitting either longitudinal or transverse waves. So various theories were proposed to account for the absence of longitudinal ether waves, one of the most prominent being Lord Kelvin's "labile ether," which was supposed to have a negative elastic modulus, and which, if not supported in some manner at the outer boundary, would tend to contract. But all these theories were more or less artificial, and none of them seemed to furnish a satisfactory solution of the difficulties which they were designed to remove.

From a study of the phenomena of electricity and magnetism evidence was accumulating that a non-material medium must be invoked to account for the fundamental facts in those fields also, but there was nothing to show that the medium which served as the basis for electrical and magnetic forces was identical with the "luminiferous ether," nor

had the study of these phenomena thrown any light on the problems which had arisen with regard to the nature of the ether.

Such was the state of affairs when James Clerk Maxwell, in 1864, by a supreme stroke of genius, advanced the theory which has served to link together two great branches of physical science and to bring order out of a chaos of apparently unrelated facts. Proceeding upon a basis of facts derived from a study of electrical and magnetic phenomena (a foundation laid for the most part by Faraday), Maxwell showed that electromagnetic disturbances, originating at any point in space, should be propagated in all directions through the ether, not instantaneously, but with a finite velocity which could be calculated by means of certain equations which he derived. The value of this velocity thus calculated came out 3×10^{10} cm. per second. At once the identity between this figure and the velocity of light as determined by several independent methods was strikingly apparent and led to the suspicion that light might be a disturbance of electromagnetic nature traveling through the ether in accordance with the laws governing such disturbances.

On the basis of this fact alone, however, the agreement between the two figures might be set down as a coincidence—a striking one, it is true, but not beyond the bounds of possibility. But Maxwell went much further than this, and showed that an oscillating electric charge should give rise to a wave motion in the ether answering in all essentials to the known properties of light waves; that these waves, consisting of an alternating electric field accompanied by an alternating magnetic field at right angles to it, and hence known as electromagnetic waves, should in case of incidence on a material medium be either reflected, refracted, or absorbed by that medium, just as light waves are.

Another very important fact was evident from Maxwell's equations—the alternating electric and magnetic fields which constitute the waves are necessarily in a plane perpendicular to the direction in which the waves are advancing; in other words, electromagnetic waves are transverse waves. Now this we have seen to be one of the essential characteristics of light waves and one which can not be satisfactorily explained on the elastic solid theory. By making the assumption that light waves are electromagnetic waves, Maxwell was thus able to account for their transverse character, to explain in a satisfactory manner all the fundamental phenomena of light, and to predict a most striking interrelation between the electrical and the optical properties of a body.

The electromagnetic theory of light as worked out by Maxwell seemed a plausible and, on the whole, a satisfactory solution of the problem as to the nature of light, but it could hardly take its place among the rank of established theories without actual experimental evidence of the existence of electromagnetic waves. Such evidence was not forthcoming until more than twenty years after Maxwell proposed the theory.

In 1888 Heinrich Hertz, in a series of brilliant researches, succeeded in producing electromagnetic waves in the laboratory and in showing that these waves possessed the characteristic properties which Maxwell had predicted. In Hertz's classic experiments two polished knobs, each attached to a rectangular metal plate, were connected to the secondary terminals of an induction coil and brought near each other. When a spark was allowed to pass between them, and a loop of wire with small adjustable spark gap was brought in the neighborhood, a tiny spark was observed in this second and independent circuit. The device for producing the original spark Hertz called the oscillator and the loop of wire the resonator. In order to prove that the effect observed was due to the radiation of some form of wave motion from the oscillator, Hertz formed stationary waves by placing a large metallic plate at some distance from the oscillator, and on moving the resonator gradually from the oscillator to the plate, found that the effect showed well-marked maxima and minima at regular intervals. A spark discharge such as is obtained in Hertz's oscillator has been shown to be oscillatory in character, and it is apparent from the experiment just described that such an oscillatory discharge sets up a wave motion of an electrical nature in the surrounding space which is reflected from the metal plate, resulting in the formation of stationary waves. By measuring the distance between successive "nodes" Hertz was able to determine the wave-length of the waves; from the dimensions and other characteristics of the oscillator it is possible to ascertain the frequency of vibration; then, knowing that in any type of wave motion the velocity is equal to the product of the frequency and the wave-length, it may be proven that the velocity of these electrical waves is 3×10^{10} cm. per second, the same as the velocity of light. Hertz showed that these waves, which were evidently the electromagnetic waves predicted by Maxwell, could be reflected, refracted and polarized; that they exhibited the phenomenon of interference; in short, that they possessed all the characteristic properties of light waves, the only difference between these waves and those which affect the optic nerve being a difference in wave-length. From a practical standpoint Hertz's discovery was of the utmost importance, for it marked the inception of modern wireless telegraphy. Other important consequences of the electromagnetic theory, which will be described presently, were confirmed later, but the original work of Hertz was sufficient to show that Maxwell's theory was in thorough accord with experimental evidence and thus to place the theory on a firm basis.

Before going further into the implications of the theory, let us see just what it postulates as to the nature of light. It is a familiar fact that a changing magnetic field gives rise to an induced electromotive force at right angles to its own direction. It is equally well known that

an electric current, or what amounts to the same thing, the motion of lines of electric force, sets up a magnetic field at right angles to the direction of these lines. An alternating electric field is then necessarily accompanied by an alternating magnetic field perpendicular to itself, and vice versa, each field attaining its maximum while the other is passing through its zero value. An electric charge at rest is surrounded by a stationary electric field; if it is caused to oscillate, it sets up an oscillating electric field at every point in the surrounding space, accompanied by an oscillating magnetic field at right angles to it. These electrical and magnetic disturbances travel outward in all directions through the ether at the enormous velocity of 300,000 km. per second, the electrical and magnetic fields being always at right angles to the direction in which the disturbance is traveling. The higher the frequency of the oscillations, the shorter will be the distance between two successive disturbances, or the wave-length. Only when the oscillations are taking place at an extremely rapid rate does the length of the waves become short enough for them to affect the human eye. Such is our conception of a light wave on the electromagnetic theory.[1]

The vast importance of the part which electromagnetic waves play in nature may be appreciated from the fact that within the group are included the entire range of radiations known as X-rays, gamma rays, ultra-violet rays, visible light of various colors, infra-red rays, heat waves, and the long waves used in wireless telegraphy. The inclusion of the first-named rays within the group must be counted one of the most remarkable achievements of experimental science in the present decade. The researches of Laue, the Braggs, and Moseley on the diffraction of X-rays by crystals have proven that X-rays consist of very short ether waves, having a wave-length of the order of magnitude of an Ångström unit (an Ångström unit being the ten-millionth part of a millimeter). In fact, the most recent work indicates that under certain conditions X-rays may be produced having a wave-length even shorter than a fifth of an Ångström unit. The gamma rays given off

[1] It will be noted that the so-called "displacement currents" which play so prominent a part in Maxwell's development of the theory have not been mentioned. It is difficult to form a clear conception of the exact nature of displacement currents, so that a discussion of them would be out of place in an elementary presentation. Moreover, however important may be their part in the mathematical development of Maxwell's equations, it is at least open to question whether we may not leave them out of account in formulating a statement of the essential characteristics of an electromagnetic wave. For certainly the outstanding features of such a wave are the alternating electric field accompanied by the alternating magnetic field. We are at liberty, if we choose, to invoke displacement currents set up by the electric field as an intermediate stage necessary to the production of the magnetic field, but the electric and magnetic fields are undoubtedly the fundamental facts upon which we are to fix our attention.

by radium and other radio-active bodies, being essentially X-rays, have wave-lengths of the same order of magnitude, but even shorter, the wave-length of the gamma rays being only about one tenth of an Ångström unit. Between the X-rays and the shortest ultra-violet rays so far obtained lies a gap, as yet unexplored. The region of very short waves of ultra-violet light, first investigated by Schumann, has been greatly extended toward the short wave-lengths by Lyman, who has been carrying on some notable work in this region and has just succeeded in measuring wave-lengths as short as 600 Ångström units or 0.00006 mm. His success in this field encourages the hope that the limit may be pushed much further and the gap entirely bridged before long. The region of the spectrum lying between 600 and 3,900 Ångström units comprises the ultra-violet rays, so-called because they lie just beyond the violet of the visible spectrum. These rays are entirely invisible to the human eye, but produce chemical action and affect a photographic plate quite readily. From 3,900 to 7,600 Ångström units (0.00039 to 0.00076 mm.) we have the visible spectrum, ranging from violet, the shortest visible rays, to red, the longest. Beyond the red end of the spectrum we have the infra-red rays, which do not affect the eye, but which convey radiant heat and are frequently known as heat waves. It is these waves, together with those of the visible spectrum, which bring to us from the sun the tremendous and unfailing stream of energy without which no life could exist on earth. This region of the spectrum has also been greatly extended in recent years, first by Rubens and his co-workers, using the method of "rest-strahlen," which enabled them to investigate waves as long as 0.06 mm., and more recently by Wood and Rubens, who used the ingenious method of focal isolation, by means of which they succeeded in obtaining the longest infra-red waves so far discovered. The longest waves obtained by this method had a wave-length of about 0.34 mm., while the shortest Hertzian waves, as produced by Righi, measure about 3 mm., leaving an unexplored region of comparatively narrow extent. Then come the electromagnetic waves produced by electrical means and varying in length all the way from the short ones produced by Righi to the very long ones used in radio-telegraphic work. The waves actually employed in this work vary from 100 meters in length or less to 10,000 meters or more.

It follows, then, that the longest known electromagnetic waves are more than one hundred trillion (10^{14}) times as long as the shortest ones. There are few of the facts revealed by the progress of modern science which make a more striking appeal to the imagination than this tremendous range of waves, varying in length all the way from those so small that hundreds of millions of them would be required to cover an inch to those several miles long; all of them essentially the same in character and obeying the same fundamental laws, but affecting us in

different ways according to their length—some of them affecting the optic nerve and revealing to our eyes all of the various colors of nature, some of them conveying to us the heat of the sun, some producing chemical effects or making an impression upon a photographic plate, some penetrating with ease bodies which are opaque to ordinary light, some healing diseases, while yet others serve to bring us messages from the ends of the earth.

It is instructive to vary our point of view by arranging this long scale in octaves, as is done in the case of the musical scale. Upon doing this we find that the whole range covers just about 48 octaves, of which the visible spectrum comprises only one! Starting with the shortest of all, the gamma rays of radium, we have a range of about four octaves, including the gamma rays and the different types of X-rays. Then comes a space of something over nine octaves, as yet unexplored. The ultra-violet group, including the waves studied by Schumann and by Lyman, follows, embracing somewhat less than three octaves. The single octave comprising the visible spectrum is next in order. The infra-red group occupies between eight and nine octaves, followed by a scant three constituting our second unexplored region. The remaining twenty or twenty-one octaves are occupied by the Hertzian waves, only the last seven, however, being made use of in wireless telegraphy. It is encouraging to note the small extent of the two gaps in our scale in comparison with the vast range which we have been able to study. It is not unreasonable to suppose that these two gaps will be entirely bridged in the near future, and that we shall be able to produce and study at will any wave-length desired from the gamma rays to the longest Hertzian waves.

There are many important consequences of the electromagnetic theory which may readily be subjected to experimental test. Chief among these are the intimate relations which according to the theory must exist between the electrical and the optical properties of a body. When waves pass from one medium to another they undergo refraction, the amount of the bending which occurs depending upon the ratio of the velocities of the waves in the two media. This ratio of velocities is termed the index of refraction of the one medium with reference to the other. But according to the electromagnetic theory the velocity of these waves in any medium is equal to $V/\sqrt{e\mu}$, where V represents the velocity of the waves in the ether, e the dielectric constant of the medium and μ its magnetic permeability. We may assume without sensible error that the magnetic permeability of any ordinary transparent medium is unity, from which it follows that $V/V' = \sqrt{e'}/\sqrt{e}$ for any two media. Since the dielectric constant of the ether may be taken as unity, it may readily be seen that the index of refraction of any material medium should be numerically equal to the square root of its dielectric constant. Thus we have an important relation between

the electrical and the optical properties of a medium, which may readily be subjected to experimental test.

In applying this relation to a specific case, however, two important facts must be kept in mind. The index of refraction of a given medium is by no means a constant, but varies with the wave-length, approaching a limiting value in the case of very long waves.[2] Neither is the so-called "dielectric constant" really a constant, as the name implies, but it varies to a certain extent with the frequency of the applied electromotive force. In actual practise it is usually determined by applying a steady electromotive force, while in the case of a light wave the alternating electric field is oscillating with an almost inconceivably high frequency. In view of these facts it is not surprising that there are many cases where the relation does not hold good when the ordinary values of the index of refraction and of the dielectric constant are used. There are several cases, however, in which we have striking agreement, even with the use of the ordinary values, as shown by the following table.

	n	$\sqrt{e}$
Air	1.000294	1.000295
Hydrogen	1.000138	1.000132
Carbon dioxide	1.000449	1.000473
Carbon bisulphide	1.637	1.634
Benzine	1.50	1.54

In the case of many substances which have values for these constants not in accord with the predictions of the theory, using the ordinary values, we find that the agreement becomes striking when we use the value for the index of refraction which applies to very long waves. Thus for water $\sqrt{e} = 8.95$ and $n = 1.334$, using yellow light. But it has been found by Fleming and Dewar that the index of refraction of water for very long waves is 8.9, approximating closely to the value of $\sqrt{e}$ given above. For flint glass $\sqrt{e}$ lies between 2.6 and 2.8 and $n =$ 1.62, using yellow light, but for long waves $n = 2.6$. So that it seems entirely probable that if we could determine the values of n and e under precisely similar conditions the relation would be exactly verified in every case.

When electromagnetic waves fall upon a body which is a non-conductor of electricity, they are refracted, the amount of deviation which

2 The variation in the index of refraction with the wave-length may be accounted for by assuming the presence in dielectrics of "bound electrons," having certain natural periods of vibration. When light waves fall upon the body, resonance effects are produced by these electrons which affect the velocity of the waves, the effect naturally being greater the more nearly the period of the waves coincides with those of the electrons. The periods of these electrons may be determined from the position of the absorption bands in the spectrum of the substance, and by modifying our theory to take into account their effect we may derive a dispersion formula which represents the index of refraction of the substance for waves of all lengths.

they suffer depending, as we have seen, upon the electrical and magnetic properties of the body. When they are incident upon a conductor, on the other hand, the alternating electric field causes rapidly alternating currents to flow in the surface of the conductor and these currents quickly absorb the energy of the waves. It is an important consequence of the electromagnetic theory, therefore, that conductors of electricity should be opaque to light and non-conductors transparent. In a general way this prediction is confirmed, for the metals, which are the best conductors we have, are also the substances most opaque to light, while many of the best insulators, such as glass, are quite transparent. Certain crystals, such as tourmaline, conduct electricity better in one direction than in another. In such crystals the transparency to light is found to vary accordingly. Most of the exceptions to the rule are explainable upon obvious grounds. For instance, water, although transparent, is a conductor of electricity under ordinary conditions. Water of absolute purity, however, is one of the best of insulators. The opacity of such non-conductors as wood, paper, etc., is explainable on the ground of lack of homogeneity in structure. Many of these substances, such as hard rubber, which are opaque to ordinary light, are quite transparent to the longer infra-red rays. Another apparent exception is found in the case of electrolytic solutions which are conductors of electricity and yet are transparent. It is to be noted, however, that the carriers of the electric current in this case are ions, having a mass very large in comparison with that of the "free electrons" which are responsible for metallic conduction, that they are consequently unable to respond to the rapid oscillations of the electric field in the electromagnetic wave and the wave is therefore not absorbed. In many cases dielectrics possess "bound" electrons or ions having characteristic periods of vibration; if a wave of precisely this frequency falls upon the substance these ions are set in vibration, thus absorbing the energy of the wave; in this way absorption lines or bands are produced in the spectrum when light is passed through the substance.

Another important consequence of the electromagnetic theory which has been fully confirmed by experiment is that light waves should exert a pressure on objects upon which they fall. Maxwell showed that electromagnetic waves must exert a pressure of definite amount, though quite small, upon a surface which absorbed them, and a pressure of double this amount on a reflecting surface. The amount of this pressure, in the case of the light we receive from the sun, he calculated to be less than a dyne per square meter of surface. On account of the smallness of the effect it eluded observation for a long time, but finally Lebedew, of Moscow, in 1900, succeeded not only in detecting this pressure due to light, but in measuring its amount, which he found to agree, within the limits of experimental error, with the value predicted by

Maxwell, thus affording one of the most notable verifications of the electromagnetic theory so far obtained. Nichols and Hull, in the United States, independently obtained the same result.

But however striking the facts we have cited, there is a link missing in the chain of evidence which supports the theory until we have succeeded in tracing the source of the electromagnetic disturbances which constitute light waves. Hertzian waves are set up by an oscillatory discharge of electricity; but where are we to find the oscillating electric charges which the electromagnetic theory calls for as the source of light waves? For many years after the theory was proposed this question was unanswerable; but with the advent of the electron theory a simple and obvious solution presented itself. According to the electron theory, the atoms of matter, instead of being the ultimate units, as was so long supposed, are made up of much smaller particles called electrons, the electron having a mass equal to about $\frac{1}{1800}$ of that of the hydrogen atom. The electron always carries a negative charge, and instead of being fixed in position is in continual and extremely rapid revolution about the positive nucleus of the atom in much the same way that the planets revolve around the sun in the solar system. Here then we have an oscillating electric charge, which must perforce set up an electromagnetic wave, on a vastly smaller scale, but otherwise the same as that produced by a Hertzian oscillator. It will be readily seen that the vibration frequency of these electrons must be almost inconceivably high, for dividing the velocity of light waves by the wave-length of red light we get for the frequency of vibration of the electron when sending out red light $\frac{3 \times 10^{10}}{7 \times 10^{-5}} = 4.28 \times 10^{14}$, or over four hundred trillion times a second, and similarly for blue light we get eight hundred trillion (8×10^{14}) times a second. When we recall the extreme smallness of the electron, even as compared with the atom, it will be apparent that there is nothing inherently improbable in these enormous values for the vibration frequency, however much they may tax the imagination, for in general the smaller the dimensions of the oscillator, the more rapid are the vibrations which it is capable of executing.

In bodies at ordinary temperatures the vibrations are much slower than this and long heat waves are sent out; as the bodies are heated and the molecules vibrate more rapidly the electrons within the atoms are also set in more rapid vibration and shorter and shorter waves are sent out; finally, when the vibration frequency becomes high enough, visible light is produced. It is a familiar fact that luminous gases give line spectra, indicating that certain definite and characteristic wave-lengths are sent out, whereas incandescent solid and liquid bodies give continuous spectra, all the wave-lengths from red to violet being represented. This is in line with what we should expect on our theory, for the electrons in the molecules of gases are free to vibrate in their natural

periods on account of the relatively long intervals elapsing between molecular collisions; whereas in solid and liquid bodies the electrons are continually being disturbed by the frequent impact of one molecule against another and so vibrate in all possible periods, thus giving rise to a continuous spectrum.

Although the electron theory contributed a great deal toward the establishment of the electromagnetic theory of light in that it indicated a probable source of the electromagnetic waves sent out from luminous bodies, we can hardly claim to have proved that the vibrating electron is the actual source of a light wave until we have actually obtained data as to certain of the most important characteristics of the vibrating source and shown that they are in accord with the data obtained as to similar properties of the electron. This has been achieved through a study of the well-known Zeeman effect. It was shown by Zeeman in 1896 that when a source of light is placed between the poles of a strong electromagnet, the lines in its spectrum break up into more or less complex groups of lines. To take one of the simplest cases, when the spark formed between cadmium electrodes is placed in a strong magnetic field and the light examined spectroscopically, the green line which is always conspicuous in the cadmium spectrum is observed to break up into two lines, one on each side of the normal position of the line, when the light is passed along the direction of the magnetic field; when viewed transversely, a triplet is formed. It may be readily shown that these are exactly the effects we should expect if we assume an electron revolving in an orbit as the source of the light waves. A magnetic field perpendicular to the plane of the revolving electron would cause a slight increase or decrease in the speed of the electron in its circular path, thus causing a slight change in the wave-length emitted with corresponding displacement of the spectrum line. The components into which the lines are broken up are found to be polarized, and by observing the direction of polarization in each component it can be shown that the vibrating source must carry a negative charge; further, by measuring the amount of separation of the components the ratio of the charge to the mass of the vibrating particle may be calculated. The value thus obtained agrees so closely with the corresponding ratio for the electron as obtained by a number of different methods that there is no longer room for doubt that light waves are electromagnetic waves set up by the revolution of the electrons within the atoms of material substances.

We may sum up the principal steps in the development of the electromagnetic theory as follows:

1. Maxwell in 1864 predicted the existence of electromagnetic waves and calculated on the basis of purely electrical data the velocity these waves should have. The resulting value proved to be the same as the velocity of light. These waves he showed should be transverse waves,

and should be capable of being reflected, refracted, and polarized just as light waves are.

2. Hertz in 1888 succeeded in producing these electromagnetic waves experimentally. Their velocity has been found to be 3×10^{10} cm. per second, the same as the velocity of light. By actual experiment Hertz showed that these waves were susceptible of reflection, refraction, and polarization and in all essential properties were identical with light waves.

3. The whole range of electromagnetic waves with which we are familiar extends all the way from the gamma rays of radium to the very long waves used in wireless telegraphy, a range of nearly 50 octaves, with only two comparatively small gaps in the scale. One of these regions of waves as yet undiscovered lies between the longest X-rays and the shortest ultra-violet rays; the other between the longest infra-red rays and the shortest Hertzian waves.

4. The electromagnetic theory calls for a very intimate relationship between the electrical and the optical properties of a body and in many cases experimental investigation gives results in close agreement with the predictions of the theory, as in the case of the connection between the opacity of a medium and its electrical conductivity, and between the index of refraction and the dielectric constant.

5. Maxwell, on the basis of his theory, predicted that light should exert a pressure on objects upon which it falls and calculated the amount of this pressure. This effect has been detected by Lebedew in Russia, and by Nichols and Hull in the United States, and found to be equal in amount to the value predicted by Maxwell.

6. The electron theory first furnished an answer to the problem as to the origin of the electromagnetic disturbances which constitute light waves, indicating the vibrating electron within the atom as the probable source. That this explanation is the correct one has been proven in a striking manner by the Zeeman effect, or resolution of spectral lines when the source of light is placed in a strong magnetic field. By means of measurements of this effect it has been proven that the vibrating source must carry a negative charge and that the amount of this charge is identical with that which the electron is known to possess.

In view of the facts which have been cited we can hardly fail to accord to the electromagnetic theory of light a place of preeminence among the achievements of physical science in the past century. Probably no other theory in the whole field of physics has served to coordinate so large a number of apparently unrelated phenomena. Two of the great branches of physics, electromagnetism and optics, have been made one; our insight into the processes of nature has been vastly broadened; and research in quest of an explanation of the more fundamental problems of optics has been both stimulated and directed by this wonderful theory, which will always stand as an enduring monument to the genius of Maxwell.